

A comparison between several vibration-powered piezoelectric generators for standalone systems

E. Lefeuvre*, A. Badel, C. Richard, L. Petit, D. Guyomar

LGEF Laboratory, INSA de Lyon, 8 rue de la Physique, 69621 Villeurbanne Cedex, France

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Abstract

This paper presents a comparison between four vibration-powered generators designed to power standalone systems, such as wireless transducers. Ambient vibrations are converted into electrical energy using piezoelectric materials. The originality of the proposed approaches is based on a particular processing of the voltage delivered by the piezoelectric material, which enhances the electromechanical conversion. The principle of each processing circuit is detailed. Experimental results confirm the predictions given by an electromechanical model: compared to usual generators, the proposed approaches dramatically increase the power of the generators.

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1. Introduction

The proliferation of transducers and sensors integrated in many systems raises the problem of the installation of wires for power supplies and data transmission. This explains the growing interest in miniature electrical generators enabling to power transducers and their associated wireless data transmission systems [1]. In many applications, the limited lifespan of batteries may induce a costly maintenance, in the case of contaminated areas for instance. Moreover, batteries dying without warning poses serious problems in safety monitoring applications. To solve this problem, sustainable power generation may be achieved in converting ambient energy into electrical energy. Some possible ambient energy sources are, for instance, thermal energy, light energy or mechanical energy. The focus here is on the transformation of mechanical vibrations, existing almost everywhere. In this field, electromagnetic and electrostatic generators have been developed [2,3]. However, piezoelectric generators are of major interest due to their solid state nature facilitating their integration and different approaches of energy harvesting using piezoelectric materials have been developed [4–6]. Since a piezoelectric element subjected to a

vibration generates an alternating voltage across its electrodes, most of the proposed electrical circuits include an AC-to-DC converter. Thus, the electrical energy is provided to a storage device, such as a capacitor or a battery, in order to feed the terminal electric load (i.e. a sensor and its associated RF emitter, for instance) under a DC voltage. The AC-to-DC converter, usually a diode bridge, is sometimes followed by a DC-to-DC converter used for power optimization or load voltage regulation [7,8].

This paper presents and compares three new techniques to the so-called “standard technique” commonly used in piezoelectric vibration-powered generators. These techniques are derived from the so-called “synchronized switch damping” (SSD), a semi-passive technique that was developed to address the problem of vibration damping in mechanical structures [9]. The SSD technique is based on a non-linear processing on the voltage delivered by the piezoelectric element. This process increases the electrically converted energy resulting from the piezoelectric mechanical loading cycle. Applied to energy harvesting, the different presented techniques increase significantly the amount of electrical energy generated by the piezoelectric insert [10,11]. The proposed processing circuits acts as electrical interfaces between the piezoelectric elements and the terminal electric load. Their respective theoretical and experimental characteristics are compared to the “standard technique”.

* Corresponding author.

E-mail address: elie.lefeuvre@insa-lyon.fr (E. Lefeuvre).

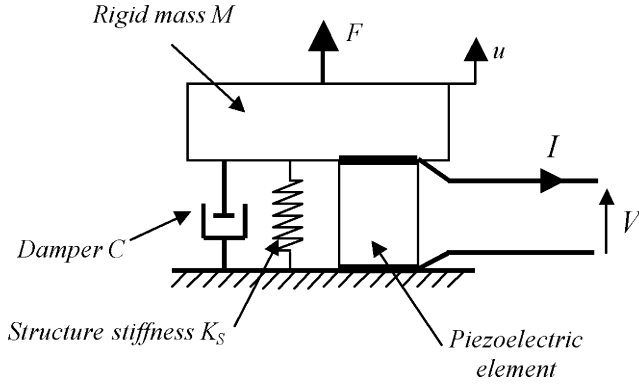


Fig. 1. Model of a vibrating structure including a piezoelectric element.

2. Electromechanical model

The aim of the model developed in this section is to enable a simple analytical calculation of the mechanical variables, as well as the electrical variables. Several mechanical architectures of vibration-based power generators are possible. In the case of piezoelectric generators, the energy conversion is maximized by a maximum deformation of the piezoelectric material. This explains that most of the reported devices are optimized for working at a resonance frequency. Near a resonance frequency, a single degree-of-freedom oscillator gives a good description of a vibrating structure. And in most cases, the problem can be simplified by considering only one vibration mode. If the mechanical structure is vibrating with little displacements for which the motion remains linear, then the structure including the piezoelectric element can be simply modeled by the {mass + piezo + spring + damper} system shown in Fig. 1.

In this basic approach, the considered electromechanical structure is a piezoelectric disk with a rigid mass M bonded on its top side. The bottom side of the disk is bonded on a reference rigid base. In addition, the stiffness and the losses of the mechanical part are, respectively, modeled by a spring K_S and viscous damper C . Although this model is not based on the experimental structure presented in Section 4, it actually gives a faithful description of the behavior of the vibration-powered electrical generator. Moreover, only a few measurements are needed to determine all the model parameters.

The rigid mass M undergoes the action of both external and internal forces. The external force F results from the mechanical excitation applied on the structure. The internal force can be separated in a restoring force F_P due to the piezoelectric element, in a restoring force due to the spring, and in a viscous force due to the damper.

The mass displacement is u . I and V are, respectively, the outgoing current and the voltage across the electrodes of the piezoelectric element. For a piezoelectric disk, the standard piezoelectric equations linking the stress T , the strain S , the electric field E and the electrical induction D are given in Eq. (1). These equations lead to the macroscopic Eq. (2) linking the mechanical variables (u and F_P) and the electrical variables (I and V), considering that the motion wavelength is much larger than the disk thickness, so that Eq. (3) are verified. In these

Table 1

Piezoelectric parameters definitions

c_{33}^E	Elastic rigidity in short circuit configuration
c_{33}^D	Elastic rigidity in open circuit configuration
ε_{33}^S	Clamped permittivity
ε_{33}^T	Free stress permittivity
e_{33}	Piezoelectric coefficient

equations, the parameters A and L are, respectively, the section and the thickness of the piezoelectric disk. In Eq. (2), K_{PE} is the stiffness of the piezoelectric disk when it is short-circuited, C_0 is its clamped capacitance and α is the force factor. Eq. (4) gives the expressions of K_{PE} , C_0 and α as a function of the piezoelectric parameters described in Table 1. The electromechanical coupling factor of the piezoelectric disk is k_t (5) and K_{PD} (6) is the disk stiffness on an open circuit

$$\begin{cases} T = c_{33}^E S - e_{33} E \\ D = e_{33} S + \varepsilon_{33}^S E \end{cases} \quad (1)$$

$$\begin{cases} F_P = K_{PE} u + \alpha V \\ I = \alpha \dot{u} - C_0 \frac{dV}{dt} \end{cases} \quad (2)$$

$$E = -\frac{V}{L}, \quad S = \frac{u}{L}, \quad I = A \frac{dD}{dt}, \quad F_P = AT \quad (3)$$

$$K_{PE} = \frac{c_{33}^E A}{L}, \quad C_0 = \frac{\varepsilon_{33}^S A}{L}, \quad \alpha = \frac{e_{33} A}{L} \quad (4)$$

$$k_t^2 = \frac{e_{33}^2}{\varepsilon_{33}^T c_{33}^E} = \frac{e_{33}^2}{\varepsilon_{33}^S c_{33}^E + e_{33}^2} = \frac{\alpha^2}{C_0 K_{PE} + \alpha^2} \quad (5)$$

$$K_{PD} = \frac{c_{33}^D A}{L} = \frac{K_{PE}}{1 - k_t^2} \quad (6)$$

As the restoring force due to the stiffness of the mechanical structure and the restoring force due to the stiffness of the piezoelectric disk act in the same way on the mass M , a global stiffness for both mechanical structure and piezoelectric disk can be defined (7) when the piezoelectric disk is on short circuit (K_E) and on an open circuit (K_D). The global electromechanical coupling factor k is then expressed in Eq. (8) as a function of the force factor α , the clamped capacitance C_0 and the global stiffness K_E

$$\begin{cases} K_E = K_{PE} + K_S \\ K_D = K_{PD} + K_S \end{cases} \quad (7)$$

$$k^2 = \frac{\alpha^2}{K_E C_0 + \alpha^2} = \frac{\alpha^2}{K_D C_0} \quad (8)$$

Eq. (9) defining the dynamic equilibrium of the system governs the displacement u of the mass M . The energy equation, Eq. (10), is obtained by multiplying both sides of Eq. (9) by the velocity and integrating over the time variable. The mechanical input energy is divided into kinetic energy, elastic energy, mechanical losses and converted energy. These energies are summarized in Table 2. The converted energy is the part of

Table 2
Energetic terms definitions

$\int F \dot{u} dt$	Input energy
$\frac{1}{2} M \dot{u}^2$	Kinetic energy
$\frac{1}{2} K_E u^2$	Elastic energy
$\int C \dot{u}^2 dt$	Mechanical losses
$\int \alpha V \dot{u} dt$	Converted energy

the mechanical energy transformed on an electrical form. This energy is the sum of the electrostatic energy stored on the capacitor C_0 of the piezoelectric disk and the energy delivered to the electric circuit connected to the electrodes (11)

$$M\ddot{u} = F - K_E u - \alpha V - C\dot{u} \quad (9)$$

$$\int F \dot{u} dt = \frac{1}{2} M \dot{u}^2 + \frac{1}{2} K_E u^2 + \int C \dot{u}^2 dt + \int \alpha V \dot{u} dt \quad (10)$$

$$\int \alpha V \dot{u} dt = \frac{1}{2} C_0 V^2 + \int VI dt \quad (11)$$

3. Interface circuits

The characteristics of the electronic load powered by the piezoelectric generator defines the voltage and the power required for a normal operating condition. The voltage required is generally a low DC voltage in the 1–20 V range, depending on the application.

The voltage delivered by the piezoelectric element is not DC but AC. Its amplitude depends on the piezoelectric element characteristics, its dimensions and also on the mechanical vibrations. The mechanical vibrations, which result from ambient vibrations, may vary in more or less important proportions. Thus, an electronic interface is needed to ensure the voltage compatibility between the terminal electric load and the piezoelectric element. An electric energy storage element, such as a capacitor or an electrochemical battery, may be also included to compensate a temporary level reduction of the environmental vibrations or to overcome a peak of the power consumed by the electronic load.

Previous work showed that the electronic interface may significantly influence the energy harvesting effectiveness [8,9]. Moreover, another power optimization way has recently been investigated with the so-called “synchronized switching harvesting with inductor (SSHI)” technique, which consists in a specific non-linear processing of the voltage delivered by the piezoelectric inserts [10,11].

This section presents four different optimization approaches and compares their respective effectiveness for harvesting energy. The first approach uses the so-called “standard circuit”, which is the most frequently used interface in piezoelectric energy harvesting devices. The three other approaches are rather new: they implement a non-linear voltage processing synchronized with the mechanical vibration.

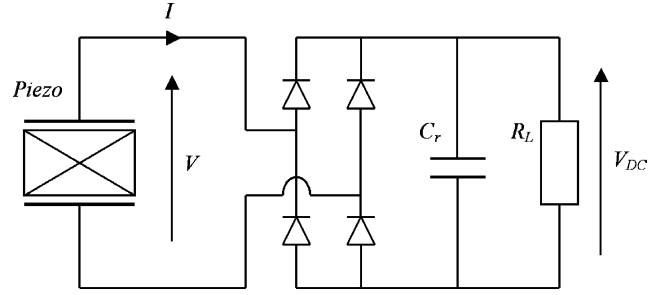


Fig. 2. Standard interface circuit.

3.1. Standard interface

The considered Standard interface circuit shown in Fig. 2 includes a diode rectifier bridge and a filter capacitor. This is practically the simplest circuit for rectifying and smoothing an alternating voltage. The terminal electric load is modeled by an equivalent resistor R_L having a power consumption equal to the average input power of the actual terminal load. The analysis of the standard circuit is presented in considering a single-mode vibration. So, the mechanical displacement u is assumed to be purely sinusoidal in steady state operation. In this condition, the open circuit voltage delivered by the piezoelectric element V is sinusoidal too. But the electrical circuit connected to the piezoelectric element changes the waveform of V . Indeed, the piezoelectric element is on an open circuit only when the rectifier bridge is blocking, therefore when the absolute value of V is lower than V_{DC} . The corresponding theoretical displacement and voltage waveforms are shown in Fig. 3. The voltage ripple of V_{DC} is here neglected. It is a good approximation on condition that the time constant $R_L C_r$ remains much larger than the mechanical vibration period.

The calculation of the harvested power for a mechanical displacement u is done in considering the piezoelectric outgoing current I given in Eq. (2).

In steady state operation, the average current through the filter capacitor C_r is null, so the absolute value of the electric charge outgoing from the piezoelectric element during a period T is

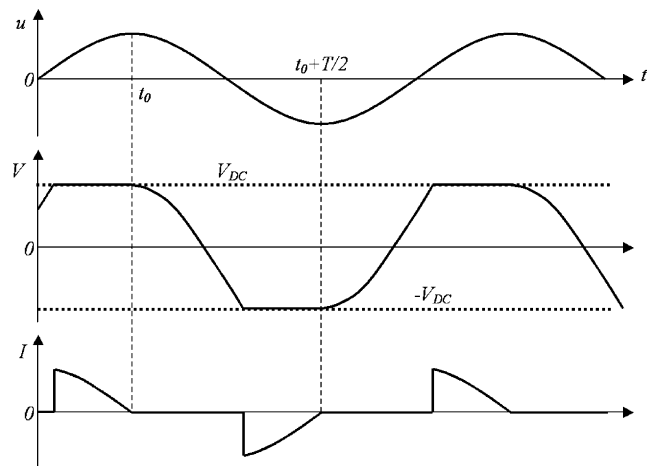


Fig. 3. Standard interface: displacement, voltage and current waveforms.

equal to the average current flowing through the load R_L . The integration of the current differential equation Eq. (2) leads to the expression of the rectified voltage V_{DC} as a function of the displacement amplitude U_M given in Eq. (12). Then, the average harvested power P is calculated in Eq. (13)

$$V_{DC} = \frac{R_L \alpha}{R_L C_0 \omega + \frac{\pi}{2}} \omega U_M \quad (12)$$

$$P = \frac{V_{DC}^2}{R_L} = \frac{R_L \alpha^2}{(R_L C_0 \omega + \frac{\pi}{2})^2} \omega^2 U_M^2 \quad (13)$$

In the case of weakly coupled energy harvesting devices, the harvested power is negligible compared to the mechanical power. So, the equivalent load resistance R_L value has no significant influence on the amplitude U_M of the mechanical displacement. In this case, the average harvested power reaches a maximum P_{MAX} for an optimal equivalent load resistance R_{OPT} , respectively, given in Eqs. (14) and (15)

$$P_{MAX} = \frac{\alpha^2 \omega}{2\pi C_0} U_M^2 \quad (14)$$

$$R_{OPT} = \frac{\pi}{2C_0 \omega} \quad (15)$$

However, it is intuitively understandable that harvesting a significant amount of the vibrational energy induces a damping effect on the mechanical system, leading to a reduction of the vibration amplitude. This effect is taken into account in considering the energy balance expressed in Eq. (10). During a particular semi-period $T/2$ (see Fig. 3), the mechanical energy provided to the system is equal to the sum of the mechanical losses and the converted energy, leading to Eq. (16).

At the resonance frequency, the displacement amplitude over the force amplitude ratio reaches a maximum, and the expression of the energy balance given in Eq. (16) can be simplified with the assumptions that the displacement u remains sinusoidal, and that the force F and the velocity are in phase (the considered resonance is not the resonance of the piezoelectric element itself, but the resonance of the global electromechanical system). These assumptions are valid while the electromechanical coupling of the system is relatively weak (so that non-linearities on the electrical variables of the system do not induce significant non-linearities on the mechanical variables), and considering that the resonator is weakly damped (that is to say resonators having practically a mechanical quality factor above 20). According to these assumptions, the analytical expression of the displacement amplitude at resonance as a function of the external force amplitude F_M given in Eq. (17) is derived from (16)

$$\int_{t_0}^{t_0+T/2} F \frac{du}{dt} dt = C \int_{t_0}^{t_0+T/2} \left(\frac{du}{dt} \right)^2 dt + \frac{V_{DC}^2}{R_L} \frac{T}{2} \quad (16)$$

$$U_M = \frac{F_M}{C\omega + \frac{2R_L \omega \alpha^2}{(R_L C_0 \omega + \pi/2)^2}} \quad (17)$$

Then, in considering Eqs. (17) and (13) it is possible to get a relation between the average harvested power P , the external

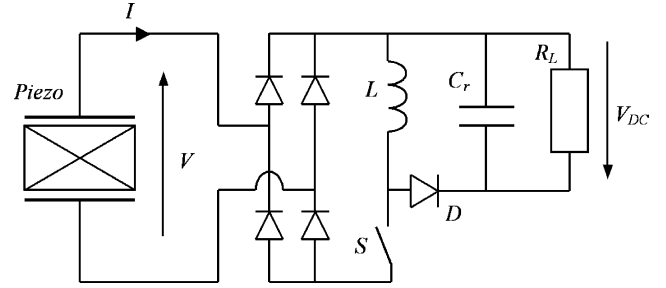


Fig. 4. Synchronous charge extraction interface circuit.

driving force amplitude F_M , the equivalent load resistance R_L and the others parameters of the system. Eq. (8) allows to include the electromechanical coupling factor in the system parameters.

3.2. Synchronous charge extraction

The synchronous charge extraction principle consists in removing periodically the electric charge accumulated on the blocking capacitor C_0 of the piezoelectric element, and to transfer the corresponding amount of electrical energy to the load or to the energy storage element. A first characteristic of this technique is that the extraction phases are synchronized with the mechanical vibration. Another peculiarity is that the piezoelectric element is let most of the time in open circuit configuration.

The proposed circuit for achieving this non-linear voltage processing is represented in Fig. 4. The charge extraction phases occur when the electronic switch S is closed: the electrical energy stored on the blocking capacitor C_0 is then transferred into the inductor L . When the electric charge is completely removed from the piezoelectric element, the switch is re-opened and the energy stored into the inductor L is transferred to the smoothing capacitor C_f through the diode D . The extraction instants are triggered on the minima and the maxima of the displacement u , synchronously with the mechanical vibration. The inductor L is chosen to get a charge extraction phase duration much shorter than the vibration period. Theoretical voltage and displacement waveforms are represented in Fig. 5.

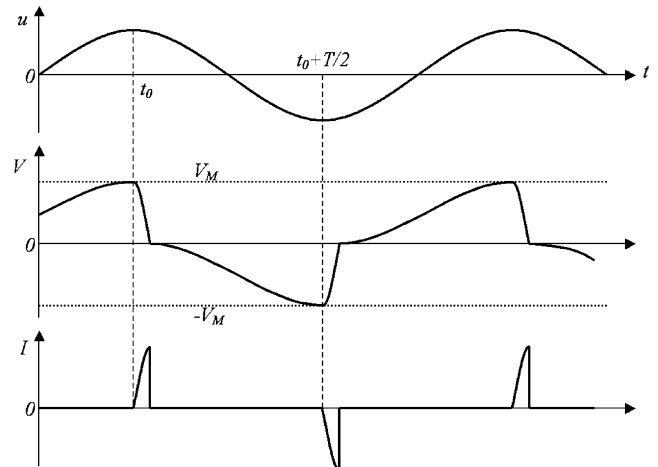


Fig. 5. Synchronous charge extraction interface: displacement, voltage and current waveforms.

Apart from the extraction phases, the rectifier is blocking and the outgoing current I is null. In this open circuit condition, the mechanical speed is related to the voltage derivate by Eq. (18). Integrating this equation over the time between instant t_1 and t_2 leads to Eq. (19) linking the voltage amplitude V_M to the displacement amplitude U_M . The electric charge extraction occurs when the absolute value of the energy stored on the piezoelectric capacitor C_0 is maximum. At these instants, the charge of C_0 is quasi-instantaneously transferred to the terminal electric load through the power converter, resulting in a cancellation of the piezoelectric voltage V . The expression of the average power delivered by the piezoelectric element is given in Eq. (20). Eqs. (19) and (20) lead to the average harvested power expression as a function of the displacement amplitude given in Eq. (21)

$$\alpha \dot{u} = C_0 \dot{V} \quad (18)$$

$$V_m = 2 \frac{\alpha}{C_0} U_M \quad (19)$$

$$P = \frac{1}{2} C_0 V_M^2 \frac{\omega}{\pi} \quad (20)$$

$$P = 2 \frac{\alpha^2 \omega}{\pi C_0} U_M^2 \quad (21)$$

To take into account the mechanical damping effect induced by this energy harvesting technique when the system is driven at resonance by a constant amplitude external force, it is considered the energy balance of the structure between instant t_1 and instant t_2 , just after each electric charge extraction. The energy provided to the system by the external force F during this half period is expressed in Eq. (22). Assuming that the displacement remains sinusoidal, the calculation of this energy balance is simplified, leading to the displacement amplitude expression U_M as a function of the external force amplitude F_M given in Eq. (23). The average harvested power as a function of the external force amplitude F_M given in Eq. (24) is deduced from Eqs. (21) and (23). Eq. (24) shows that it exists a particular relation between the electromechanical parameters given in Eq. (25), for which the average harvested power reaches a maximum. The corresponding harvested power P_{MAX} is given in Eq. (26)

$$\int_{t_0}^{t_0+T/2} F \dot{u} dt = C \int_{t_0}^{t_0+T/2} \dot{u}^2 dt + \frac{2\alpha^2}{C_0} U_M^2 \quad (22)$$

$$U_M = \frac{F_M}{C\omega + \frac{4\alpha^2}{\pi C_0}} \quad (23)$$

$$P = 2 \frac{\alpha^2 \omega}{\pi C_0} \frac{F_M^2}{\left(C\omega + \frac{4\alpha^2}{\pi C_0}\right)^2} \quad (24)$$

$$\frac{\alpha^2}{C_0} = \frac{\pi C \omega}{4} \quad (25)$$

$$P_{MAX} = \frac{F_M^2}{8C} \quad (26)$$

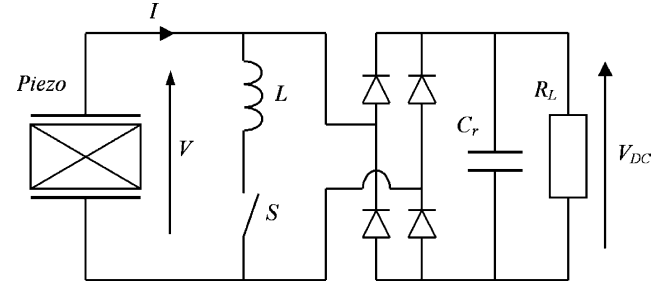


Fig. 6. Parallel-SSHI interface circuit.

3.3. Parallel-SSHI

This Parallel-SSHI interface is composed of a non-linear processing circuit connected in parallel with the piezoelectric element electrodes and the input of the rectifier bridge [10,11], as shown in Fig. 6. The non-linear processing circuit is only composed of an inductor L in series with an electronic switch S . The electronic switch is briefly turned on when the mechanical displacement reaches a maximum or a minimum. At these triggering times, an oscillating electrical circuit $L-C_0$ is established. The electrical oscillation period is chosen much smaller than the mechanical vibration period T . The switch is turned off after a half electrical period, resulting in a quasi-instantaneous inversion of the voltage V . The corresponding theoretical displacement and voltages waveforms are shown in Fig. 7.

When the switch is turned on, the absolute value of the voltage V remains lower than the rectified voltage V_{DC} so the rectifier bridge is blocking. However, the voltage polarity inversion is not perfect, meaning that the non-linear process induces small energy losses. Most of the voltage inversion losses are due to the circuit composed of the inductor in series with the switch. A small part may also be radiated in the mechanical system. The inversion losses are modeled by the electrical quality factor Q_i of the electrical oscillator. The relation between Q_i and the voltages of the piezoelectric element before and after the inversion process (V_{DC} and V_m , respectively) is given in Eq. (27)

$$V_m = -V_{DC} e^{-\pi/2 Q_i} \quad (27)$$

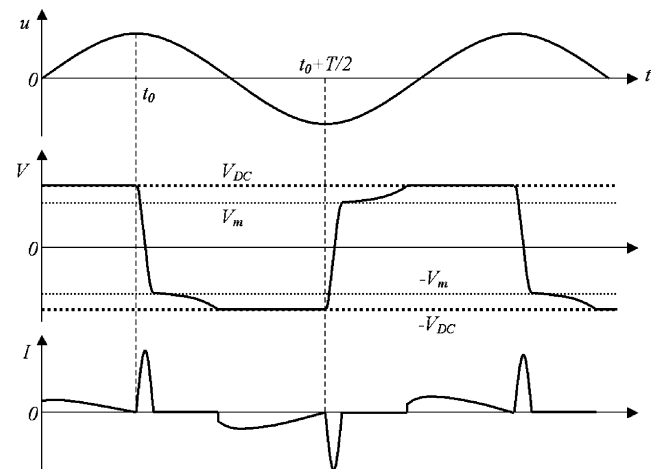


Fig. 7. Parallel-SSHI interface: displacement and voltages waveforms.

$$\int_{t_0}^{t_0+T/2} I dt + \int_{t_0}^{t_0+T/2} I_S dt = \frac{V_{DC}}{R_L} \frac{T}{2} \quad (28)$$

The electric charge received by the terminal load equivalent resistor R_L during a half mechanical period $T/2$ is calculated in Eq. (28). The second integral of this equation corresponds to the charge stored on the capacitor C_0 before the voltage inversion plus the charge stored on C_0 after the inversion, whose expression is given by Eq. (29). The integration of the piezoelectric outgoing current given by Eq. (2) in taking into account the SSHI non-linear process leads to the expression of the load voltage V_{DC} as a function of the displacement amplitude U_M given by Eq. (30)

$$\int_{t_0}^{t_0+T/2} I_S dt = C_0 V_{DC} (1 + e^{-\pi/2 Q_i}) \quad (29)$$

$$V_{DC} = \frac{2R_L \alpha \omega}{R_L C_0 (1 + e^{-\pi/2 Q_i}) \omega + \pi} U_M \quad (30)$$

The average harvested power P is expressed in Eq. (31). With a given mechanical vibration amplitude U_M , the average harvested power reaches a maximum value P_{MAX} , whose expression is given in Eq. (32), for an optimal equivalent load resistance R_{OPT} given by Eq. (33). These expressions show that the harvested power depends strongly on the voltage inversion efficiency, quantified by the electrical quality factor Q_i . If Q_i is much larger than $\pi/2$, the maximum average harvested power P_{MAX} becomes roughly proportional to this quality factor. For example, if this factor would be multiplied by two, the harvested power would be also multiplied by two for a given amplitude of mechanical displacement. Thus, according to Eq. (32) the electrical quality factor Q_i should be as big as possible to get as much as possible electrical power with a given amount of piezoelectric material. This factor is practically limited by the losses of the electrical LC_0 oscillator, which are mainly located in the inductor (Joule losses and ferromagnetic losses). The quality factor of the experimental setup presented in Section 4 is variable between $Q_i = 0$ and 13. Increasing this value above 20 would require a very low losses inductor. It would lead in practice to a bulky, heavy and expensive component

$$P = \frac{V_{DC}^2}{R_L} = \frac{4R_L \alpha \omega^2}{(R_L C_0 \omega (1 - e^{-\pi/2 Q_i}) + \pi)^2} U_M^2 \quad (31)$$

$$P_{MAX} = \frac{\alpha^2 \omega U_M^2}{\pi C_0 (1 - e^{-\pi/2 Q_i})} \quad (32)$$

$$R_{OPT} = \frac{\pi}{C_0 \omega (1 - e^{-\pi/2 Q_i})} \quad (33)$$

The expression of the vibration amplitude at resonance as a function of the amplitude F_M of the external driving force is given in Eq. (34). Eqs. (31) and (34) lead to a direct relation between the harvested average power and the amplitude of the external driving force

$$U_M = \frac{F_M}{C \omega + \frac{4R_L \alpha \omega^2}{\pi} \frac{R_L C_0 (1 - e^{-\pi/2 Q_i}) \omega + 2\pi}{(R_L C_0 (1 - e^{-\pi/2 Q_i}) \omega + \pi)^2}} \quad (34)$$

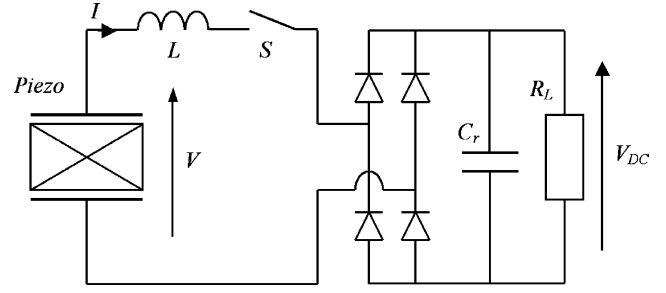


Fig. 8. Series-SSHI interface circuit.

3.4. Series-SSHI

The Series-SSHI interface circuit is similar to the Parallel-SSHI circuit, but instead of connecting the {switch + inductor} dipole in parallel with the piezoelectric element and the rectifier input, this dipole is connected in series, as shown in Fig. 8.

The switch control is the same as the control described in the case of the Parallel-SSHI circuit. Most of the time, the piezoelectric element is in open circuit configuration. Each time the switch is closing, a part of the energy stored in the blocking capacitor C_0 is transferred to the capacitor C_r through the rectifier bridge. At those instants, the voltage inversions of V occur. The voltages and displacement waveforms are drawn in Fig. 9. Eq. (35) gives the relation between the piezoelectric voltages V_M and V_m before and after the inversion process, the rectified voltage V_{DC} and the electrical quality factor Q_i . The open circuit evolution of the piezoelectric voltage V between two voltage inversions gives another relation between V_M and V_m given in Eq. (36). Equality of the input energy of the rectifier and the energy consumed by the equivalent load resistance R_L during a semi-period of vibration $T/2$ leads to Eq. (37). Starting from (35)–(37), the load voltage V_{DC} is expressed as a function of the displacement amplitude U_M , the equivalent load resistor R_L and the system parameters in Eq. (38). The average harvested power expression given in Eq. (39) may be calculated using the load voltage expression (38)

$$V_m - V_{DC} = -(V_M - V_{DC})e^{-\pi/2 Q_i} \quad (35)$$

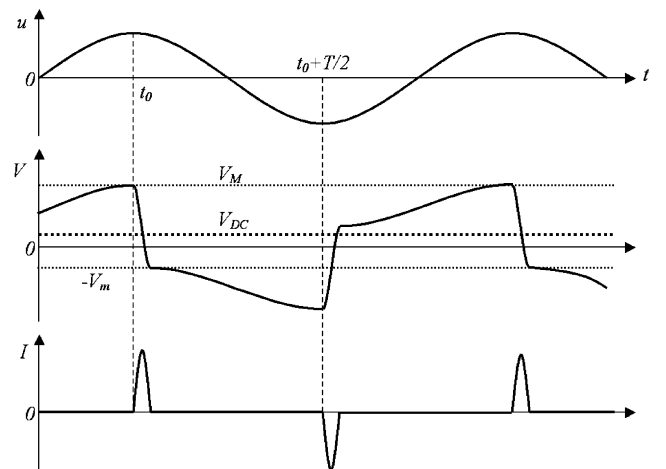


Fig. 9. Series-SSHI interface: displacement and voltages waveforms.

$$V_M = -V_m + \frac{2\alpha}{C_0} U_M \quad (36)$$

$$V_{DC} \int_{t_0}^{t_0+T/2} I dt = C_0 V_{DC} (V_M + V_m) = \frac{\pi}{R_L \omega} V_{DC}^2 \quad (37)$$

$$V_{DC} = \frac{2\alpha U_M R_L \omega (1 + e^{-\pi/2 Q_i})}{\pi (1 - e^{-\pi/2 Q_i}) + 2 R_L C_0 \omega (1 + e^{-\pi/2 Q_i})} \quad (38)$$

For a constant displacement amplitude U_M , the average harvested power reaches the maximum value P_{MAX} given in Eq. (40) for an optimal equivalent load resistance R_{OPT} given by Eq. (41)

$$P = \frac{V_{DC}^2}{R} \quad (39)$$

$$P_{MAX} = \frac{\alpha^2 U_M^2 \omega}{2\pi C_0} \frac{1 + e^{-\pi/2 Q_i}}{1 - e^{-\pi/2 Q_i}} \quad (40)$$

$$R_{OPT} = \frac{\pi}{2C_0 \omega} \frac{1 - e^{-\pi/2 Q_i}}{1 + e^{-\pi/2 Q_i}} \quad (41)$$

The relation between the external force amplitude F_M driving the system at resonance, the displacement amplitude U_M , the piezoelectric voltage maximum value V_M and the load voltage V_{DC} given in Eq. (42) is deduced from the energy balance of the electromechanical system on a vibration period. Expressions of V_{DC} and V_M as a function of U_M can be derived from (35)–(38), and replaced in (42) in order link the driving force amplitude to the displacement amplitude at resonance. Thus, it is possible to take the damping effect induced by the energy harvesting process into account

$$F_M = \omega C U_M + \frac{2V_{DC}^2}{R U_M} + \frac{C_0}{\pi} \frac{(V_M - V_{DC})^2}{U_M} (1 - e^{-\pi/2 Q_i}) \quad (42)$$

4. Theoretical and experimental results

4.1. Experimental setup

The mechanical part of the experimental setup is a structure composed of a 180 mm long cantilever steel beam clamped at one end on a rigid base, as shown in Fig. 10. The piezoelectric material used is a PZT P1-89 (hard material) manufactured by Saint-Gobain Quartz & Silice (France). Eighteen piezoelectric inserts are bonded on the beam surface, nine on each side, close to the clamped end where the strain is maximum for the first flexural mode. All the piezoelectric inserts are electrically connected in parallel. The poling direction is perpendicular to the surface of the beam, so the lateral coupling k_{31} mainly drives the piezoelectric response. The cantilever free-end displacement is measured with an inductive proximity sensor. The dimensions of the beam and the PZT inserts are given in Table 3. The vibration is driven by an electromagnet that generates an alternative force on the beam free-end, controlled through a waveform generator and a power amplifier.

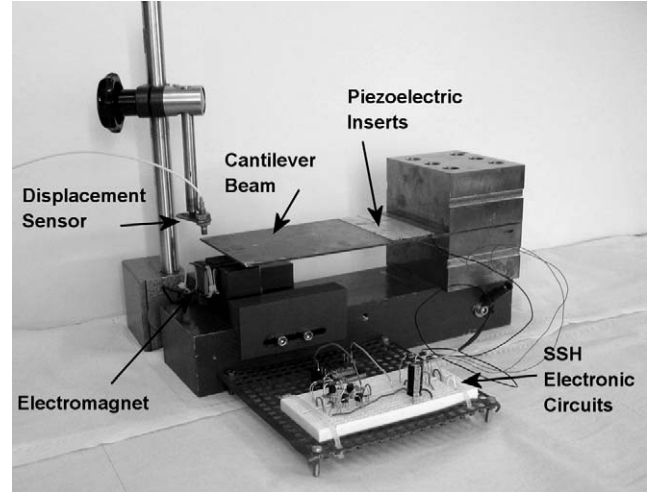


Fig. 10. Experimental setup.

Table 3
Experimental setup description

Beam material	XC65 (blue steel)
Beam dimensions	180 mm × 90 mm × 2 mm
First bending mode frequency	56 Hz
PZT ceramic type	P1-89 (QS-France)
PZT insert dimensions	30 mm × 10 mm × 0.3 mm
PZT inserts quantity	18

4.2. Parameters identification

The considered piezoelectric structure is more complex than the single-mode resonator described in Section 2. And the various parameters cannot be simply obtained from the properties of the piezoelectric inserts. However, the structure presents all the features of the piezoelectric electromechanical resonator defined in Section 2.

Its properties can therefore be identified using the experimental measurements defined in Table 4. The model parameters are then deduced from the measurements using Eq. (43).

The identified model describes then the experimental setup behavior around the considered resonance frequency, which is, in this case, the first flexural mode. Numerical data corresponding to the experimental electromechanical setup are summarized in Table 5. The maximum value of the experimental electromechanical coupling factor squared is 0.0142. The electromechanical coupling factor is then varied by connecting a capacitor C_{ext} in parallel with the terminal electrodes of the piezoelectric elements. The new electromechanical coupling factor value can be

Table 4
Measurements

f_0	Short circuit resonance frequency
f_1	Open circuit resonance frequency
ξ	Open circuit damping coefficient
γ	Open circuit piezoelectric voltage to the beam free-end displacement ratio
C_0	Clamped capacitance of the piezoelectric element

Table 5
Model parameters

C_0	170 nF
α	$4.14 \times 10^{-3} \text{ N V}^{-1}$
k^2	0.0142
K_E	$7.11 \times 10^{-3} \text{ N m}^{-1}$
M	57.1 g
C	$0.0777 \text{ N m}^{-1} \text{ s}^{-1}$

determined using Eq. (8) while replacing the blocking capacitor C_0 value with $(C_0 + C_{\text{ext}})$. This way to vary the electromechanical coupling is actually equivalent to a change in the number of used piezoelectric elements, but it is simpler to implement

$$\alpha = \gamma C_0, \quad K_E = \alpha \gamma \frac{f_0^2}{f_1^2 - f_0^2}, \quad M = \frac{K_E}{4\pi^2 f_0^2},$$

$$C = 4\pi \xi M f_1 \quad (43)$$

4.3. Results and discussion

This section presents the theoretical characteristics of a piezoelectric generator using successively the four interfaces presented in Section 3. The performances are compared in two different cases of operation: the power generator is first driven with a constant force amplitude, then it is driven with a constant displacement amplitude.

4.3.1. Generator driven with a constant force amplitude

As a first theoretical comparison, variations of the electrical average power delivered by the piezoelectric element as a

function of the load resistance value and as a function of the electromechanical coupling factor squared are represented in Fig. 11. In each case, the mechanical resonator is driven at resonance with a 0.045 N driving force amplitude. The force frequency is accurately tuned at the resonance frequency, which is influenced by the load resistance and by the electromechanical coupling factor. The frequency remains actually between 55 and 57 Hz in every cases.

The electromechanical coupling factor is an important parameter to consider in the design of a piezoelectric vibration-powered generator because it influences significantly the system performances. This factor squared is related to the piezoelectric material quantity. They are roughly proportional in some particular configurations. According to Fig. 11, the considered energy harvesting systems have not the same behavior as a function of the electromechanical coupling.

Fig. 11(a) exhibits the particular behavior of the Standard interface: for weak electromechanical couplings, this technique presents one particular load resistance leading to a maximum of the harvested power. In this domain, the matching load resistance is the same as the R_{OPT} value calculated in the case of a vibrating system having a constant displacement amplitude given in Eq. (15). A behavior change appears for higher values of the electromechanical coupling, where there are two different values of the matching load resistance [10,11].

Fig. 11(b) shows that the power harvested by the system using the synchronous charge extraction technique is not influenced by the load resistance value. In this mode of operation (driving force of constant amplitude), a particular value of the electromechanical coupling factor leads to a maximum of the average harvested power. The fact that the harvested power is not always on the increase with the coupling factor is a particularly non-intuitive

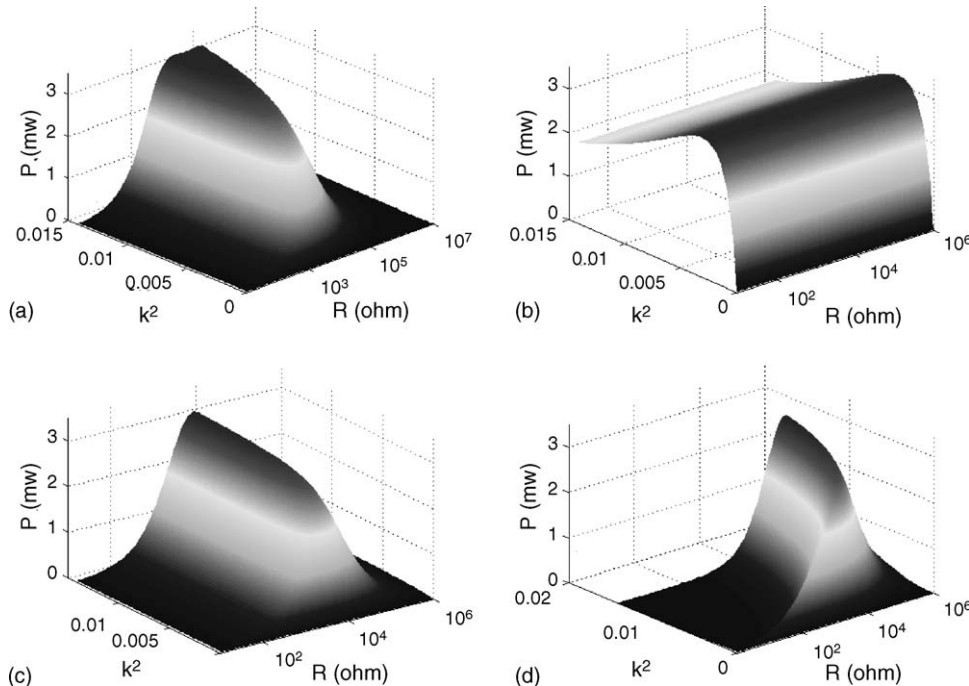


Fig. 11. Harvested electrical power, the generator being driven by a force of constant amplitude at resonance, using the (a) Standard interface, (b) Synchronous Charge Extraction interface, (c) Series-SSHI interface and (d) Parallel-SSHI interface.

behavior. A physical interpretation can be done in considering the coupling coefficient influence on the mechanical damping. According to Eqs. (8) and (23), for a given force amplitude F_M the displacement amplitude U_M and the electromechanical coupling vary oppositely. In the weak electromechanical coupling domain the damping effect is also weak. The displacement amplitude allows the structure to receive power from the external driving force. So, in this domain it is understandable that the harvested power increases when the electromechanical coupling increases. In the strong electromechanical couplings domain, the damping effect is significant. And seeing that the external driving force has a constant amplitude, the mechanical power received by the structure may be lower than in the weak coupling domain because of a strong displacement amplitude reduction. Thus, in this domain the harvested power may decrease when the electromechanical coupling increases. A theoretical justification is given by the expression of the harvested average power as a function of the force amplitude and the electromechanical coupling factor (44) derived from Eqs. (8) and (24). According to this expression, the harvested average power reaches a maximum P_{MAX} given in Eq. (26) for a critical value, $k_{critical}$, of the electromechanical coupling factor given in Eq. (45)

$$P = \frac{2F_M^2 K_D k^2 \omega}{(\pi C \omega + 4K_D k^2)^2} \quad (44)$$

$$k_{critical} = \sqrt{\frac{\pi C \omega}{K_D}} \quad (45)$$

The harvested power characteristics plotted in Fig. 11(c) and (d) show the similar behavior of the system using the Series-SSHI and the Parallel-SSHI interfaces. However, the matching load resistance is lower in the case of the Series-SSHI interface than in the case of the Parallel-SSHI interface.

The theoretical maximum harvested powers using each technique are plotted in Fig. 12, the vibrating system being driven at resonance frequency by a 0.045 N force amplitude. This figure clears-up the global behavior shown by Fig. 11: the maximal power of 3.2 mW is harvested with the Synchronized Charge Extraction interface, with $k^2 = 0.003$. The three other interfaces tend to harvest the same power when k^2 tends towards 1. For weak couplings (i.e. k^2 below 0.006 in the case of the considered setup), the SSHI interfaces are more effective than the Standard interface. But the Synchronized Charge Extraction technique appears actually as the most effective technique for power and active material optimization. All these predictions are confirmed by the experimental results given in Fig. 12(b). The corresponding theoretical and experimental beam free-end displacement amplitude variations as a function of the electromechanical coupling factor squared are, respectively, plotted in Fig. 13(a) and (b). The damping effect induced by the different energy harvesting processes appears clearly. In the particular case of the synchronous charge extraction technique, the displacement amplitude tends to zero as the electromechanical coupling factor tends to 1. With the three other techniques, the displacement amplitudes tend to the same, not null, value. These behaviors are consistent with the powers variations observed in the different

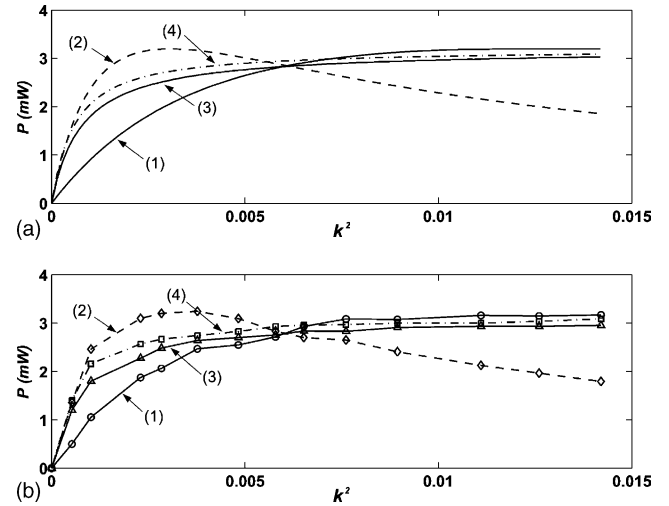


Fig. 12. (a) Theoretical and (b) experimental harvested electrical power as a function of the electromechanical coupling factor squared, the generator driven at resonance by a 0.045 N force amplitude, with the: (1) Standard interface, (2) Synchronous Charge Extraction interface, (3) Series-SSHI interface and (4) Parallel-SSHI interface.

cases: the power harvested with the synchronous charge extraction technique tends to zero as the electromechanical coupling factor tends to 1, whereas the harvested powers tend to the same maximum value in the other cases (Fig. 12).

4.3.2. Generator driven with a constant displacement amplitude

This operating condition is typical of weakly coupled systems and non-resonant systems. It is experimentally reproduced here in tuning the driving force in order to overcome the mechanical damping effect of energy harvesting. The results presented in Fig. 14(a) and (b) are obtained with the maximum electromechanical coupling ($k^2 = 0.0142$) and with a 2 mm displacement

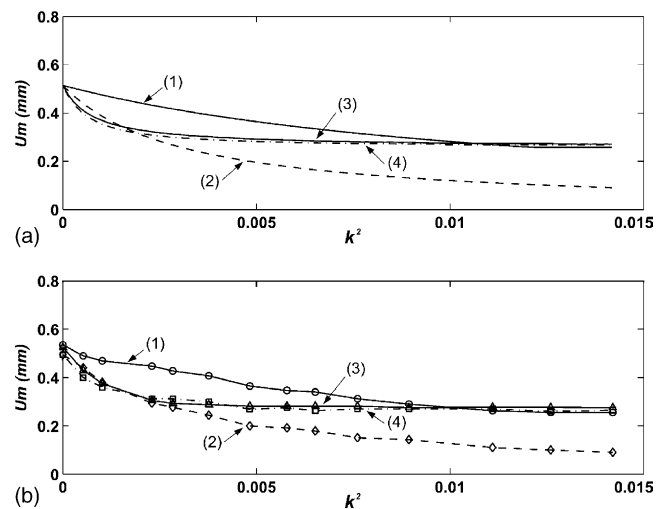


Fig. 13. (a) Theoretical and (b) experimental beam free-end displacement amplitude as a function of the electromechanical coupling factor squared, the generator driven at resonance by a 0.045 N force amplitude, with the: (1) Standard interface, (2) Synchronous Charge Extraction interface, (3) Series-SSHI interface and (4) Parallel-SSHI interface.

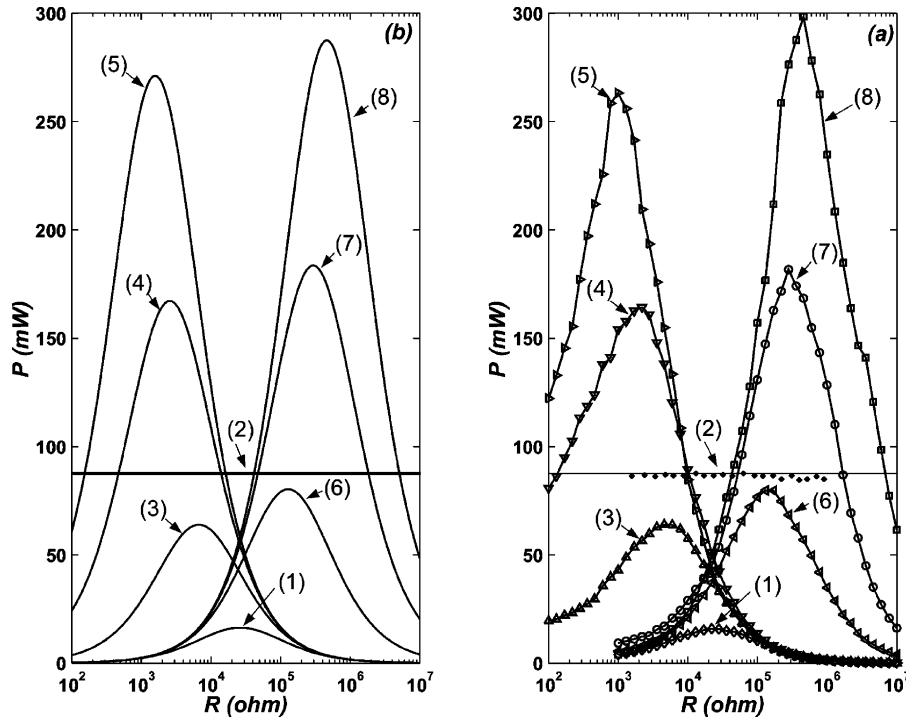


Fig. 14. (a) Theoretical and (b) experimental harvested electrical powers as a function of the load resistance, with a 2 mm displacement amplitude of the beam free-end at 56 Hz, with the: (1) Standard interface; (2) Synchronized Charge Extraction interface; Series-SSHI interface with (3) $Q_i = 5$, (4) $Q_i = 8$, (5) $Q_i = 13$; Parallel-SSHI interface with (6) $Q_i = 5$, (7) $Q_i = 8$ and (8) $Q_i = 13$.

amplitude of the beam free-end at 56 Hz. In this case of operation, the powers harvested with the three new techniques are strongly increased by comparison with the standard technique. With the Synchronized Charge Extraction technique, the harvested power is theoretically multiplied by a factor 6.5 compared to the maximum average power obtained with the standard technique. This power gain remains theoretically constant for any load resistance value. This remarkable property has been experimentally verified for load resistance values between 2 k Ω and 1 M Ω . Theoretical predictions and experimental results show that gain factors up to 15 can be realistically considered in the case of the Series-SSHI and Parallel-SSHI techniques. As shown in Fig. 14, the maximum power remains strongly dependent on the quality factor Q_i . And, as explained in Section 3.3, the electrical quality factor value is mainly limited in practice by the inductor losses. The harvested power is also strongly influenced by the load resistance value, which must be finely tuned to get the maximum of power. The Series-SSHI interface leads to low matching load impedances, whereas the Parallel-SSHI interface leads to higher matching load impedances. Thus, in this case of operation (system driven with a constant displacement amplitude) both interfaces have the same behavior with respect to the load resistance, like in the case of the system driven with a constant force amplitude. The matching load resistance value of the Standard interface is in-between.

4.3.3. Discussion

The theoretical and experimental results presented in the previous subsections allow to discuss the opportunity to use each technique. In the first operating case considered, the genera-

tor is driven with a constant force amplitude and the mechanical damping effect induced by energy harvesting is considered. This corresponds in particular to vibration-powered generators using the seismic (or inertial) principle: the driving force is provided by a seismic mass and is proportional to the acceleration resulting from the ambient vibrations. The energy harvesting process may induce a significant damping effect on the seismic mass motion.

In this operating case, the four techniques have the same maximum harvested power, but each maximum is not reached for the same value of the electromechanical coupling factor. With the Standard interface, the Series-SSHI interface and the Parallel-SSHI interface, the harvested power tends to increase as the electromechanical coupling factor increases. Practically, there is not any significant increase of the respective harvested powers above $k^2 = 0.01$ (in the case of the presented experimental setup). Whereas in the case of the Synchronous Charge Extraction interface, the harvested average power reaches a maximum for a particular value of the electromechanical coupling ($k^2 = 0.003$ for the presented experimental setup), and then it decreases. Thus, the Synchronous Charge Extraction technique enables a significant reduction of the required amount of piezoelectric material: since the amount of material is roughly proportional to k^2 , the piezoelectric material volume required to maximize the harvested power with this technique is practically divided by a factor 3 compared to the three other techniques requirements. However, the three other techniques have not the same effectiveness. For instance, according to Fig. 12, with an electromechanical coupling factor squared of 0.002, the Parallel-SSHI, the Series-SSHI and the Standard interfaces harvest, respectively, 83, 76

and 43% of the power harvested with the Synchronous Charge Extraction interface.

In the second operating case considered, the generator is driven with a constant mechanical displacement amplitude. In other words, the mechanical damping effect induced by energy harvesting is neglected. This corresponds in particular to vibration-powered generators using directly the strain of the host structure. In this case, the harvested energy remains relatively weak compared to the global vibratory energy of the host structure, and the strain of the host structure is practically not influenced by the energy harvesting process. In this operating case, the Parallel-SSHI and the Series-SSHI may bring an impressive improvement of the electromechanical power conversion. The power gain depends on the power losses in the inductor used in these interfaces. Theoretical and experimental results presented herein show that it is possible to reach a power gain of 17 by comparison with the standard technique. From another point of view, the SSHI techniques may reduce significantly the required amount of piezoelectric material for a given application: by a factor up to 17 according to the presented results. In the case of the Synchronous Charge Extraction technique, the gain factor is 4 by comparison with the standard technique.

The last point of this discussion concerns the power consumed by each interface. The results presented herein do not give the actual useful electric power, but the electric power extracted from the piezoelectric inserts, calculated and measured in each case from V and I parameters. The electrical losses due to the inductor L used in the case of the Parallel-SSHI and the Series-SSHI interfaces (modeled by the quality factor Q_i) are also taken into account. But the power consumed by the switches control circuit of each interface, plus the losses of the electronic circuit performing the Synchronous Charge Extraction must be withdrawn to get the useful power. Control circuits of the SSHI interfaces and of the Synchronized Charge Extraction interface consuming less than 5% of the extracted power have been experimented successfully. And the efficiency of the electronic power circuit of the Synchronous Charge Extraction is practically better than 70%, depending on the electronic circuits technology. Recent progress in the domain of very low power electronic circuits, designed for power management of portable electronic devices, allow to consider the 95–99% efficiency range as a realistic goal.

5. Conclusion

Over the past few years, there has been a surge of research in the area of energy harvesting. Since mechanical vibrations exist in most systems, many works focused on vibration-driven generators. In this field, the piezoelectric materials turned out well suited for the mechanical-to-electrical energy conversion. Design of the mechanical system that transmits the surrounding vibratory energy to the piezoelectric material is a critical point. It contributes in particular to the determination of the amount and the shape of the active material.

The electrical interface which connects the piezoelectric element to the terminal electric load is another critical point in

the optimization of a piezoelectric energy harvesting system. Power optimization with the Standard interface, which is used in most of the energy harvesting devices reported in literature, requires an impedance adaptation of the terminal electric load. This problem is avoided with the new Synchronized Charge Extraction technique presented in this paper. Moreover, this technique increases the harvested power by a factor 4. Two others power optimization techniques, referred to as Parallel-SSHI and Series-SSHI, may dramatically increase the harvested power in the case of weakly coupled systems or in the case of non-resonant systems. According to the theoretical and experimental results, the power gain of these techniques is above 15 by comparison with the standard technique. From another point of view, the Synchronized Charge Extraction, the Parallel-SSHI and the Series-SSHI interfaces allow a significant reduction of the amount of piezoelectric material required for harvesting a given power.

Thus, the techniques proposed in this paper bring significant compactness and effectiveness improvements of vibration-based piezoelectric generators, supporting the development of future infinite lifespan smart power sources.

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Biographies

Elie Lefevre was born in France, in 1971. He received the BS and MS degrees in electrical engineering, respectively, from Paris-XI University, Paris, France, in 1994 and from Institut National Polytechnique de Toulouse, Toulouse, France, in 1996. At the same time, he was student at the electrical engineering Department of Ecole Normale Supérieure de Cachan, Cachan, France. He prepared his PhD degree at Laval University of Québec, Que., Canada, and at the Institut National Polytechnique de Toulouse, France. He received the diploma from both universities in 2001 for his work on power electronics converters topologies. In 2002, he got a position of assistant professor at Institut National des Sciences Appliquées (INSA) de Lyon, Lyon, France, and he joined the Laboratoire de Génie Electrique et Ferroélectricité. His present research interests include piezoelectric systems, energy harvesting, vibration control and acoustic noise reduction.

Adrien Badel was born in France, in 1979. He graduated from Institut National des Sciences Appliquées (INSA) de Lyon, Lyon, France, in electrical engineering in 2002 with an MS degree, and is currently working toward the PhD degree in mechanic and materials at the Laboratoire de Génie Electrique et Ferroélectricité of INSA de Lyon, Lyon, France. His main field of interest focuses on non-linear switched piezo devices for vibration damping and energy harvesting.

Claude Richard was born in 1965. He graduated from Institut National des Sciences Appliquées (INSA) de Lyon, Lyon, France, in electrical engineering in 1988 and obtained his PhD degree in acoustics from INSA in 1992 for a study on piezoelectric composite hydrophones. After a postdoctoral study on 1-3 piezocomposite materials at the Underwater Sound Reference Detachment of the Naval Research Laboratory (NRL-USRD) Orlando, FL, in 1993, he got a position at INSA where he worked on the applications of piezoelectric ceramics since 1994. He is currently a professor of electrical engineering at

INSA where he manages the Electroactive Systems Team of the Laboratoire de Génie Electrique et Ferroélectricité. His research interests include non-linear switched piezo devices for vibration damping and energy harvesting, 1-3 piezocomposites (dice and fill and piezo fiber composite types), power applications of piezoelectrics and material characterization.

Lionel Petit received the MS degree in 1992 from University Claude Bernard, Lyon, France, and the PhD in acoustics in 1996 from the Institut National des Sciences appliquées de Lyon, Lyon, France, for his work on piezoelectric motors. He joined the Laboratoire de Génie Electrique et Ferroélectricité (INSA Lyon) where is associate professor since 1998. His current research interests include development and characterization of piezoactive systems.

Daniel Guyomar received a degree in physics from Amiens University, Amiens, France, an engineering and a doctor-engineer degree in acoustics from Compiègne University, Compiègne, France, and a PhD degree in physics from Paris VII University, Paris, France. In 1982–1983, he worked as a research associate in fluid dynamics at the University of Southern California (USC), Los Angeles. He was a National Research Council Awardee (1983–1984) detached at the Monterey Naval Postgraduate School, CA, to develop transient wave propagation modeling. He was hired in 1984 by Schlumberger to lead several projects dealing with borehole imaging, then he moved to Thomson Submarine activities in 1987 to manage the research activities in the field of underwater acoustics. In 1992, Dr. Guyomar cocreated the Techsonic Company, which is involved in research, development and production of piezoelectric and ultrasonic devices. He is presently a full-time university professor at Institut National des Sciences Appliquées (INSA) de Lyon, Lyon, France, where he manages the Laboratoire de Génie Electrique et Ferroélectricité and is consultant for several companies. His present research interests are in the field of piezo-material characterization, piezo-actuators, acoustics, power ultrasonics, vibration control and energy harvesting.